



SAPIENZA
UNIVERSITÀ DI ROMA



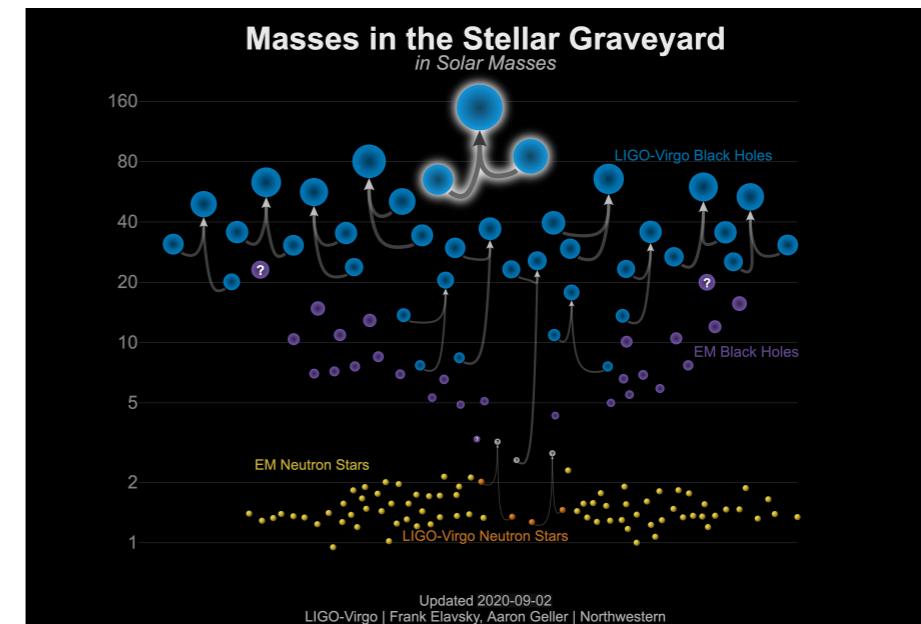
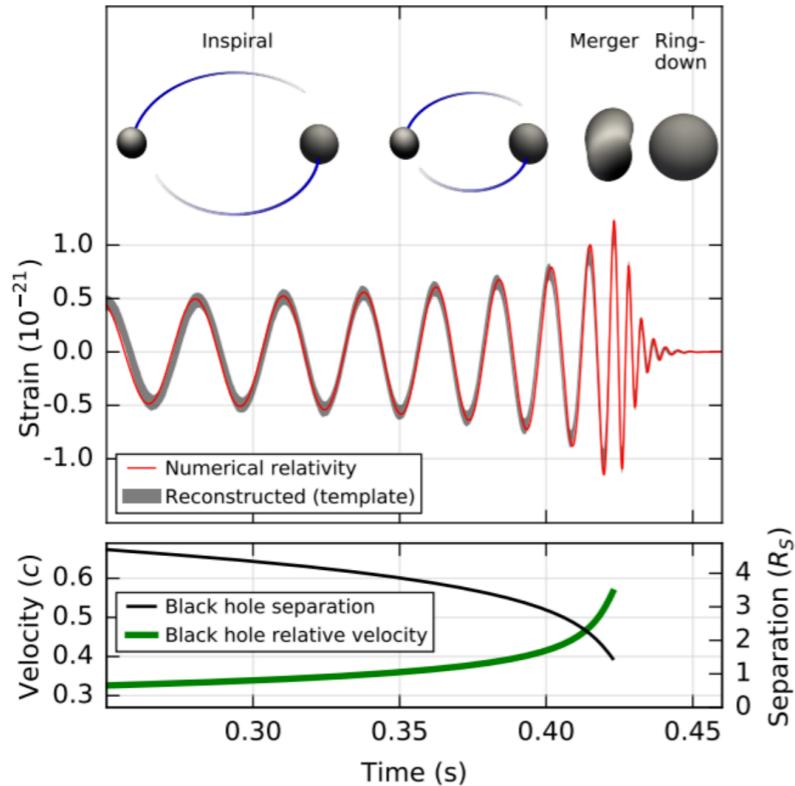
DarkGRA The logo for DarkGRA, featuring a stylized blue and white sphere.

Black-hole microstate spectroscopy: ringdown, quasinormal modes, and echoes

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w/ Massimo Bianchi, Dario Consoli, Alfredo Grillo, Jose
Francisco Morales, Paolo Pani, Guilherme Raposo

arXiv:2103.10960

Gravitational wave astronomy

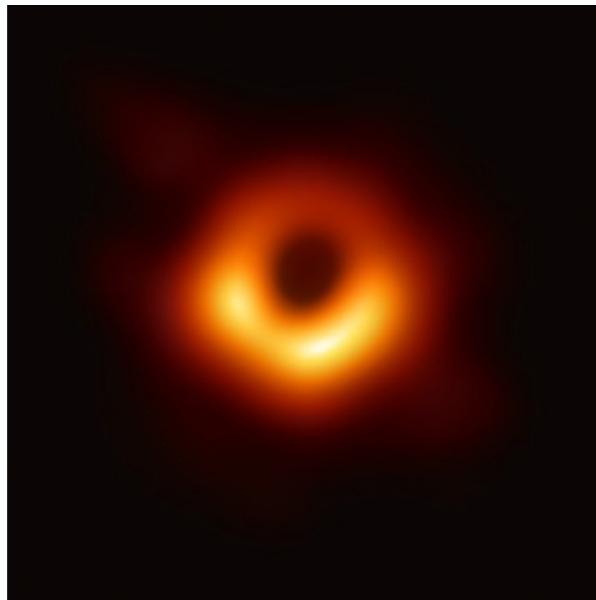


- What we can learn from gravitational waves.
 - Origin of black holes/ binaries, Primordial black hole, equation of state of neutron star, BH as a particle detector, Test of gravitational theory, et al

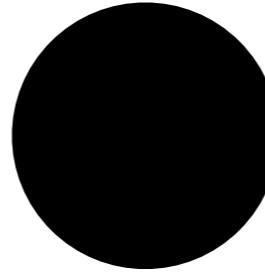
Exotic compact object

Q. Can we distinguish BH from exotic compact object using gravitational waves ?

→ Test of general relativity

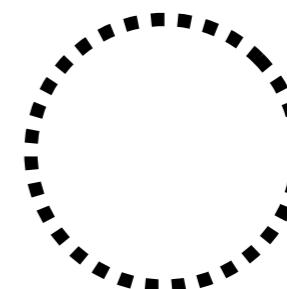


is



BH

or



ECO

?

- **Exotic compact object (ECO)**

- Boson stars, gravastars, wormholes, firewalls, **Fuzzballs** et al.
- Important parameters
 - ▶ Compactness : C
 - ▶ Reflectivity : \mathcal{R}

$$C_{\text{BH}} = 1$$

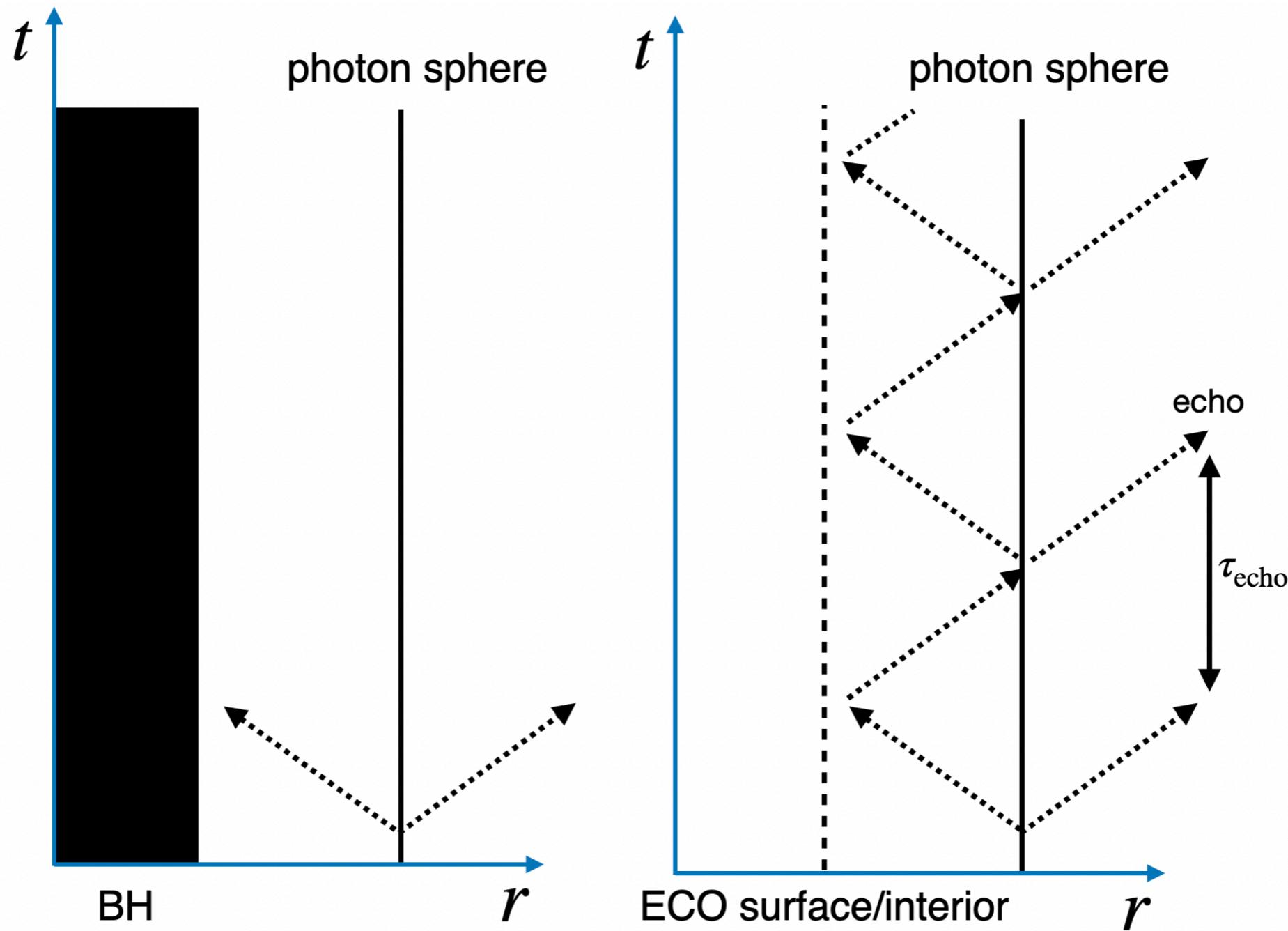
$$\mathcal{R}_{\text{BH}} = 0$$

$$\text{cf: } C = \frac{2M}{R}$$

Black hole vs ECO

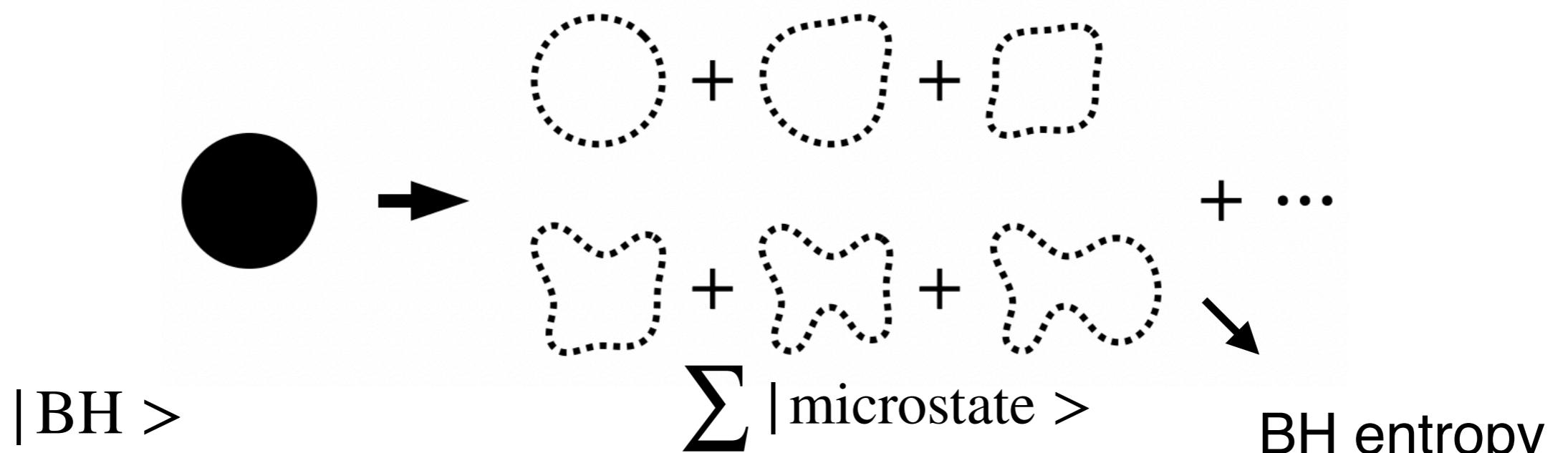
$C > 2/3$

- If ECO is enough compact, it can have the photon sphere.
- General properties of gravitational waves from BH and ECO



Fuzzball proposal

- BHs in GR have many theoretical problems.
 - How to describe the BH singularity.
 - Information paradox ?
 - What is the origin of the BH entropy ? et al
- String theory provides horizon-scale microstructure that replaces the black hole. (Fuzzball proposal)



- BH horizon
- curvature singularity

- horizonless
- smooth (no singularities in 5-dim)
- same charge as corresponding BH

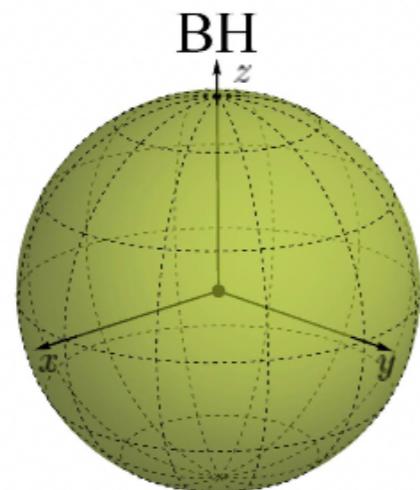
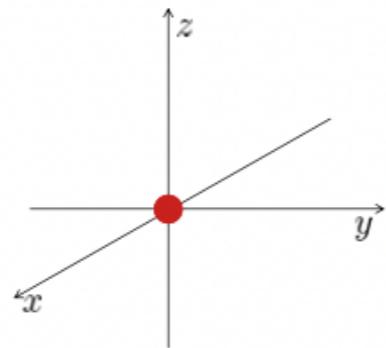
Fuzzball proposal

- We focus on the microstate geometry corresponding 4-charge BH with 3 electric and 1 magnetic charge. M.Bianch et.al (2017)

4 charge BH

$$ds^2 = -f(r)dt^2 + f(r)^{-1}\delta_{ij}dx^i dx^j$$

$$f(r) = (H_1 H_2 H_3 H_4)^{-1/2} \quad H_A = 1 + \frac{Q_A}{r}$$

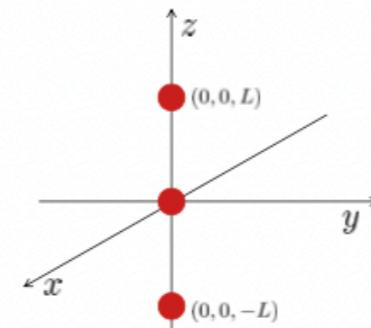


microstate geometry

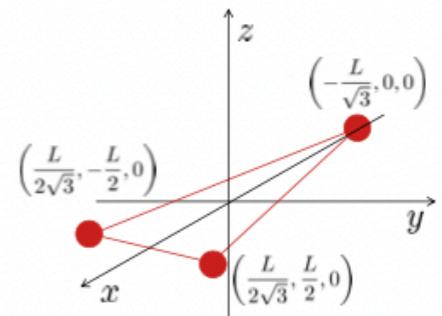
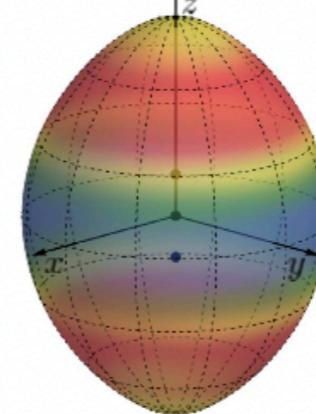
$$ds^2 = -e^{2U}(dt^2 + \omega)^2 + e^{-2U}\delta_{ij}dx^i dx^j$$

$$e^{2U}, \omega = \dots$$

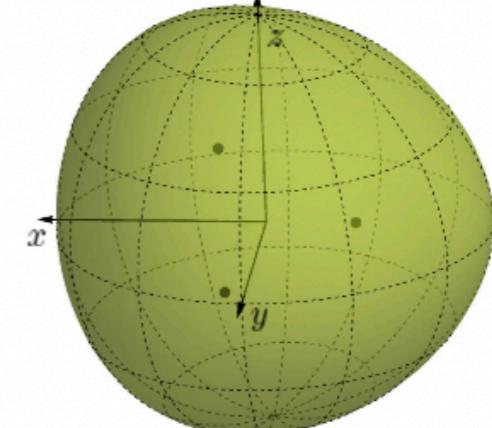
3-center geometry



Axisymmetric

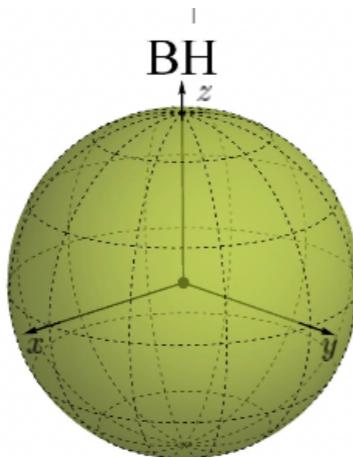


Scaling



What we want to do

- What is the typical gravitational waves from Fuzzball ?
- How different they are from corresponding BH ?
 - $\square \Phi = 0 \rightarrow$ ring down? echos ? QNM ?

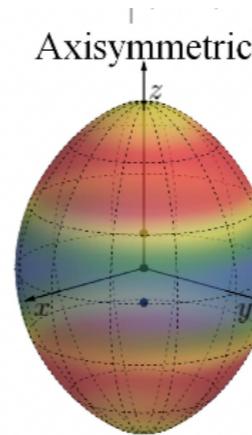
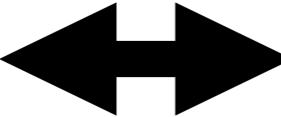


Spherical symmetry

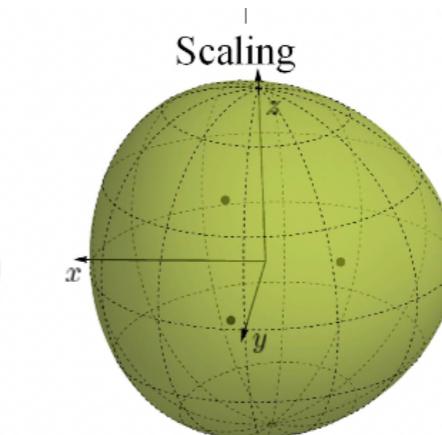
- WKB approximation
- 1+1 time evolution
- direct integration



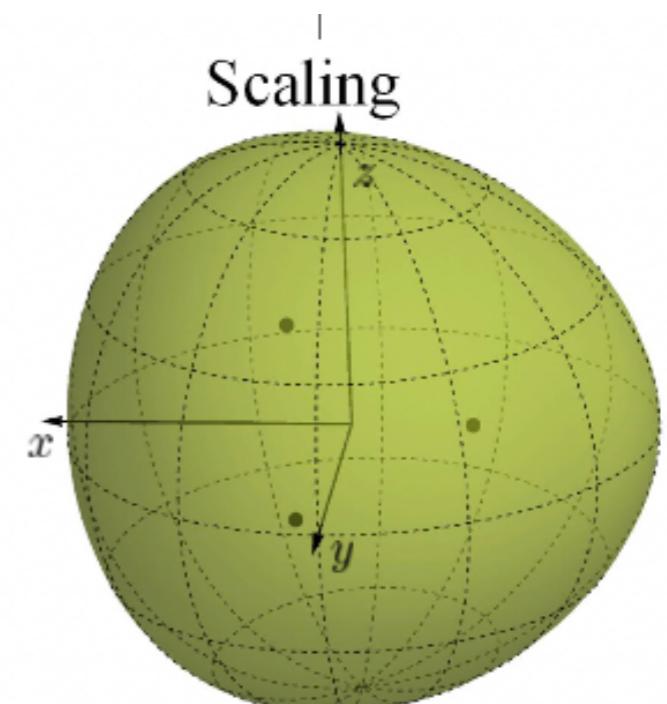
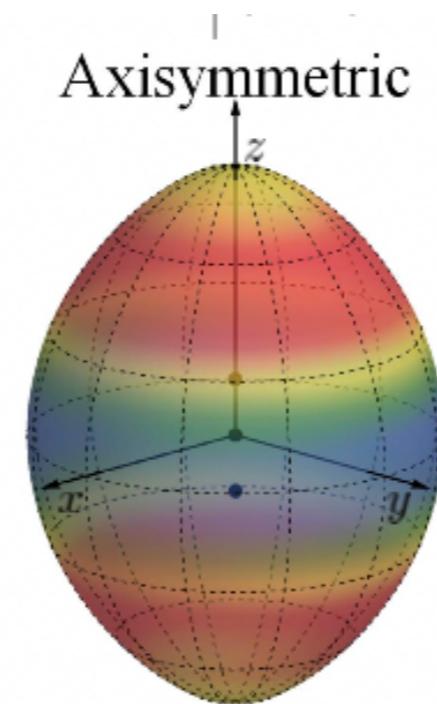
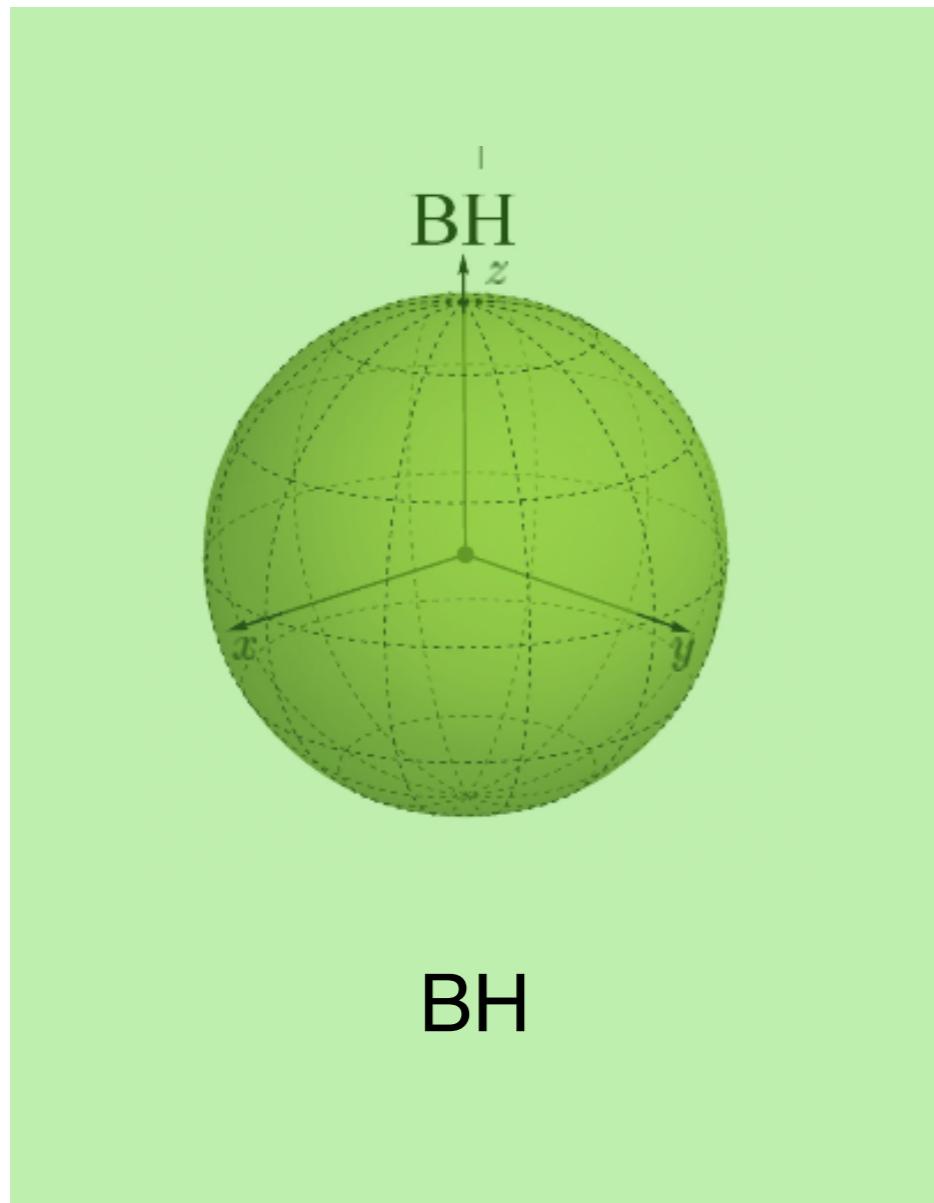
QNM of 4 charge BH



- WKB approximation
- 3+1 numerical simulation



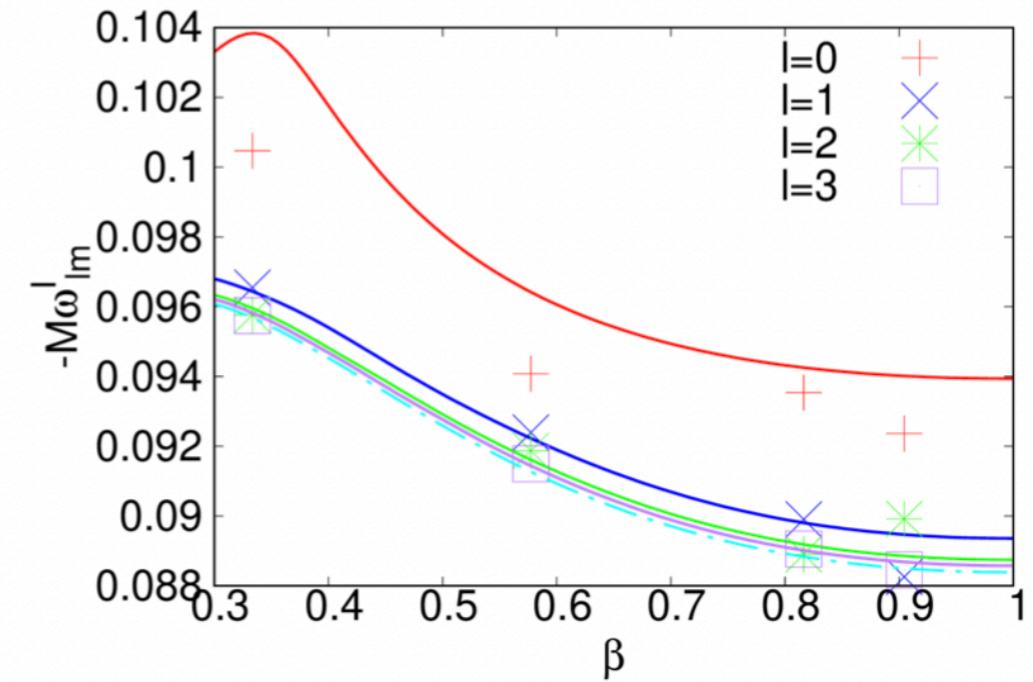
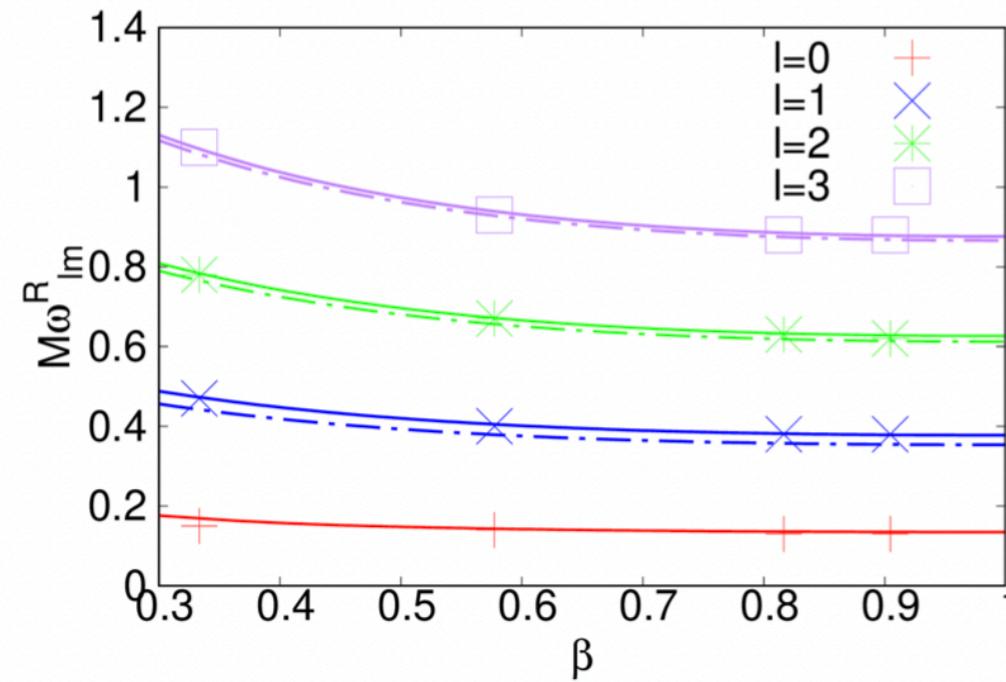
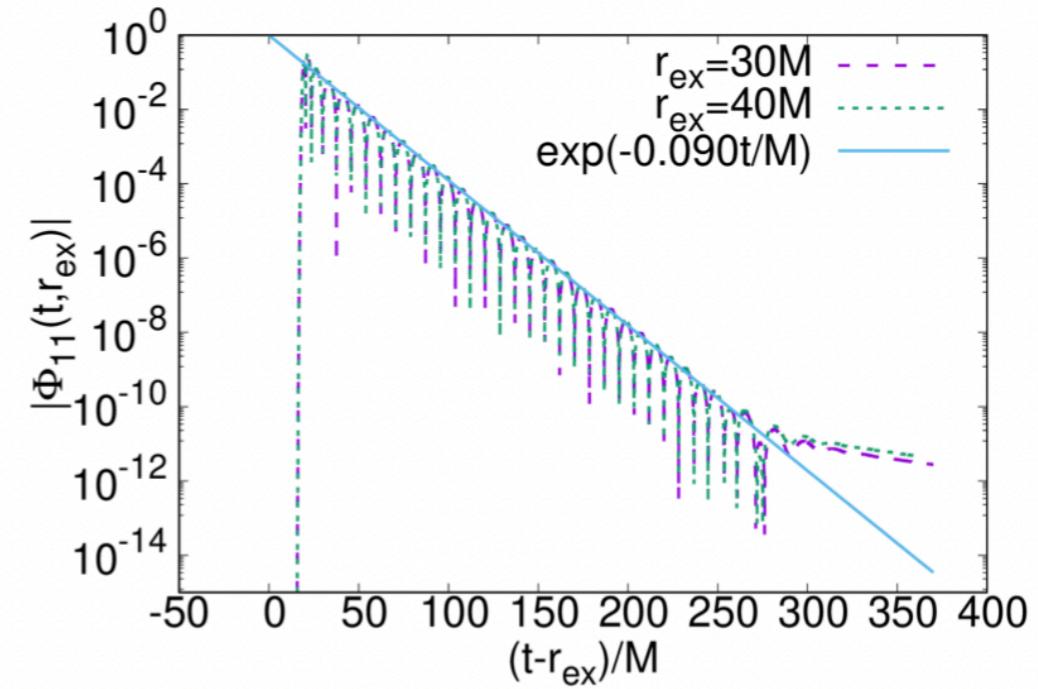
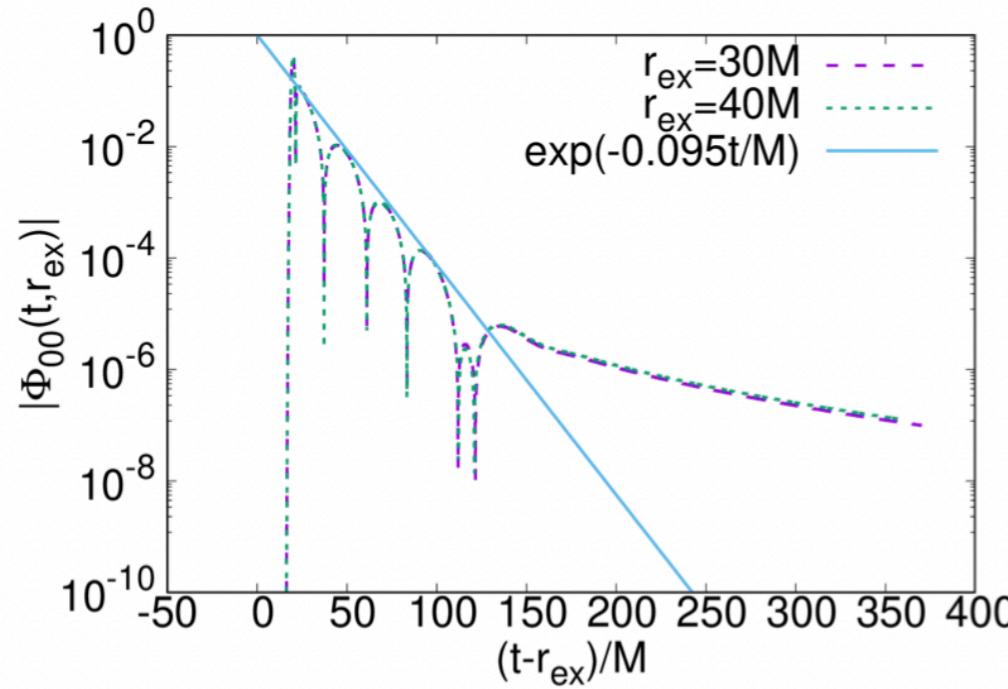
ringdown, echo, QNM (?)



Fuzzball

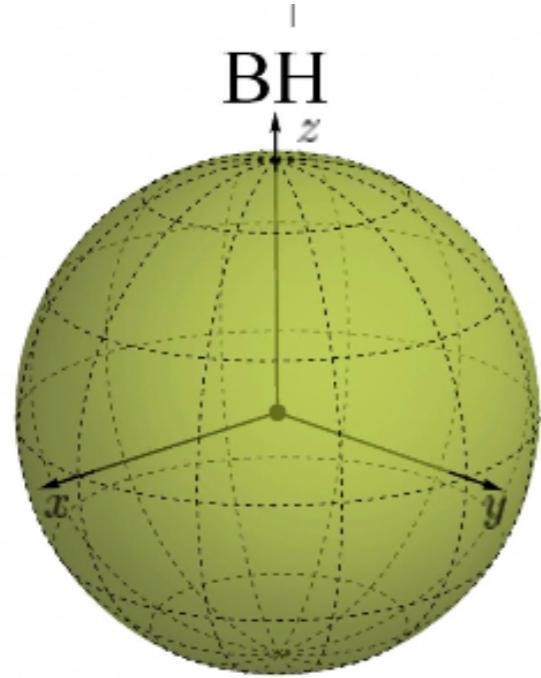
QNM in 4 charge BH

$$\beta = \sqrt{Q_2/Q_1}, Q_1 = Q_3, Q_2 = Q_4$$

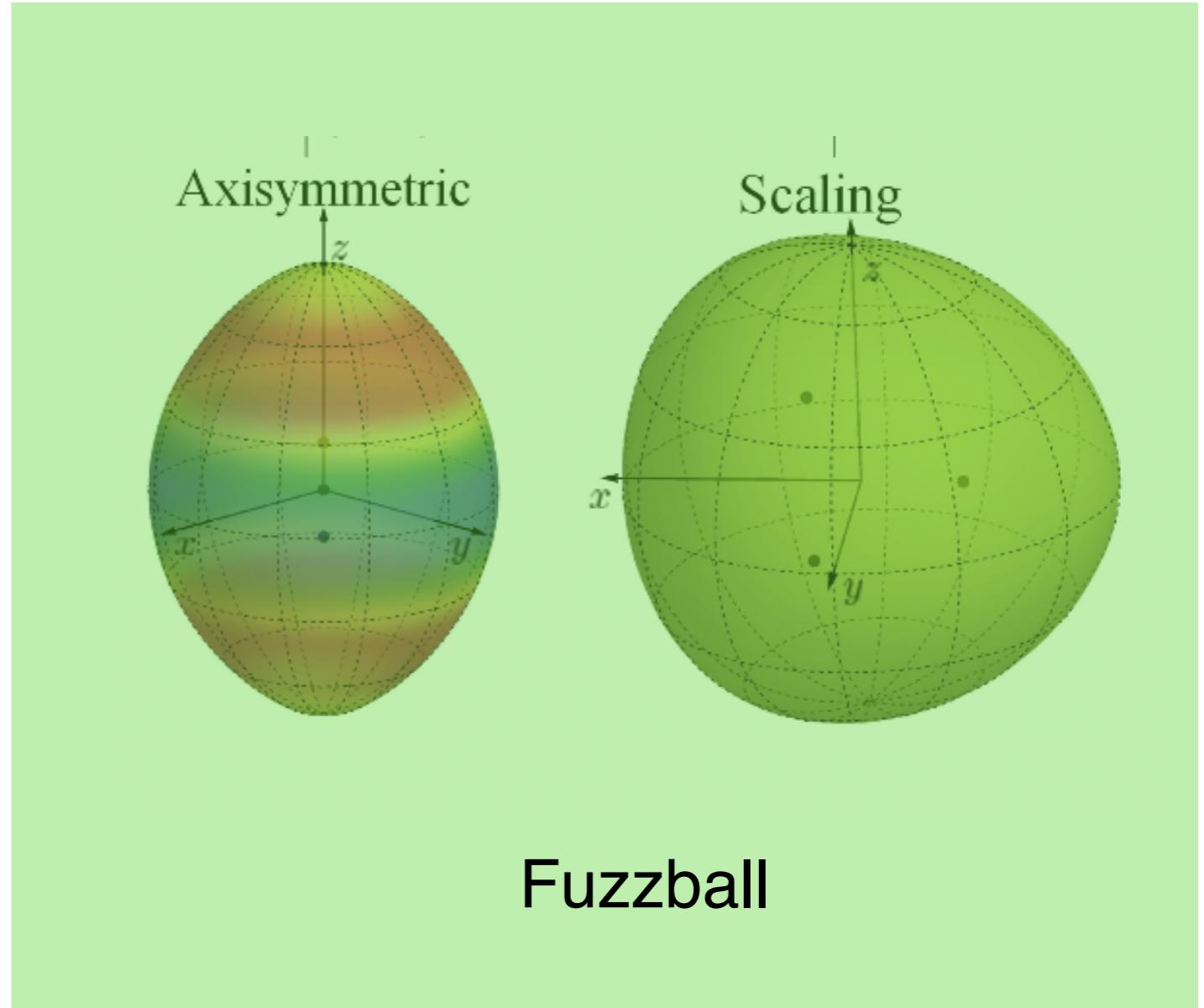


solid line : direct int
dot-dashed line : WKB

$\omega_I M \sim \mathcal{O}(0.1)$



BH



Fuzzball

Photon sphere around Fuzzball

- WKB approximation

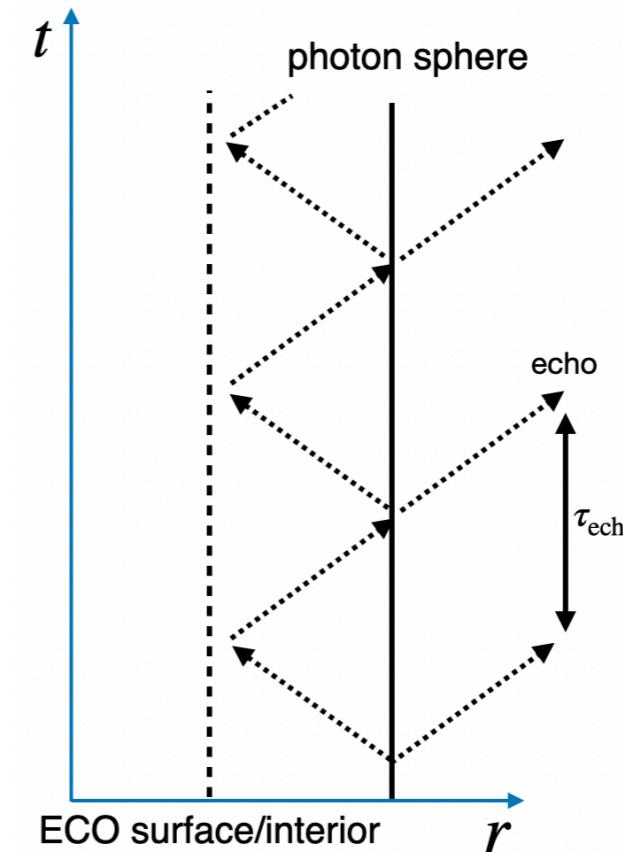
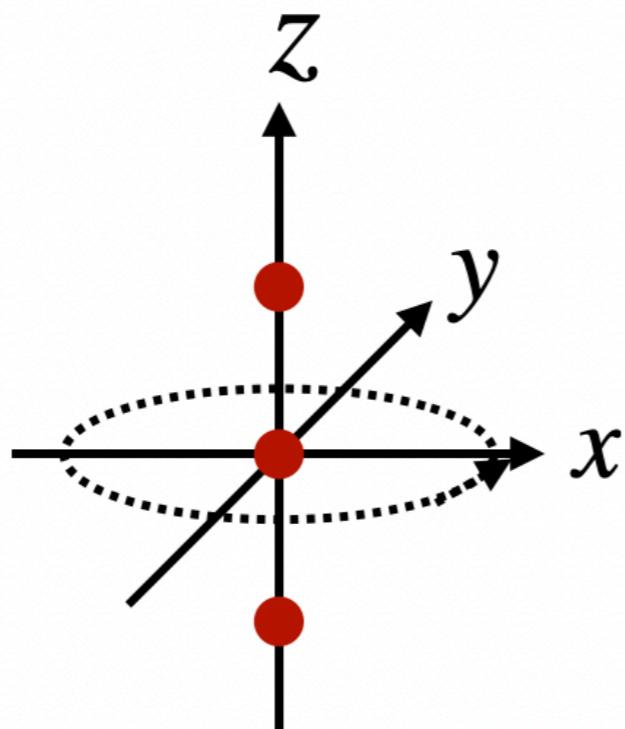
- The unstable photon sphere in axisymmetric fuzzball.

$$\text{Re}(\omega_{\text{QNM}}) \leftrightarrow \text{orbital frequency}$$

$$\text{Im}(\omega_{\text{QNM}}) \leftrightarrow \text{Lyapunov exponent}$$

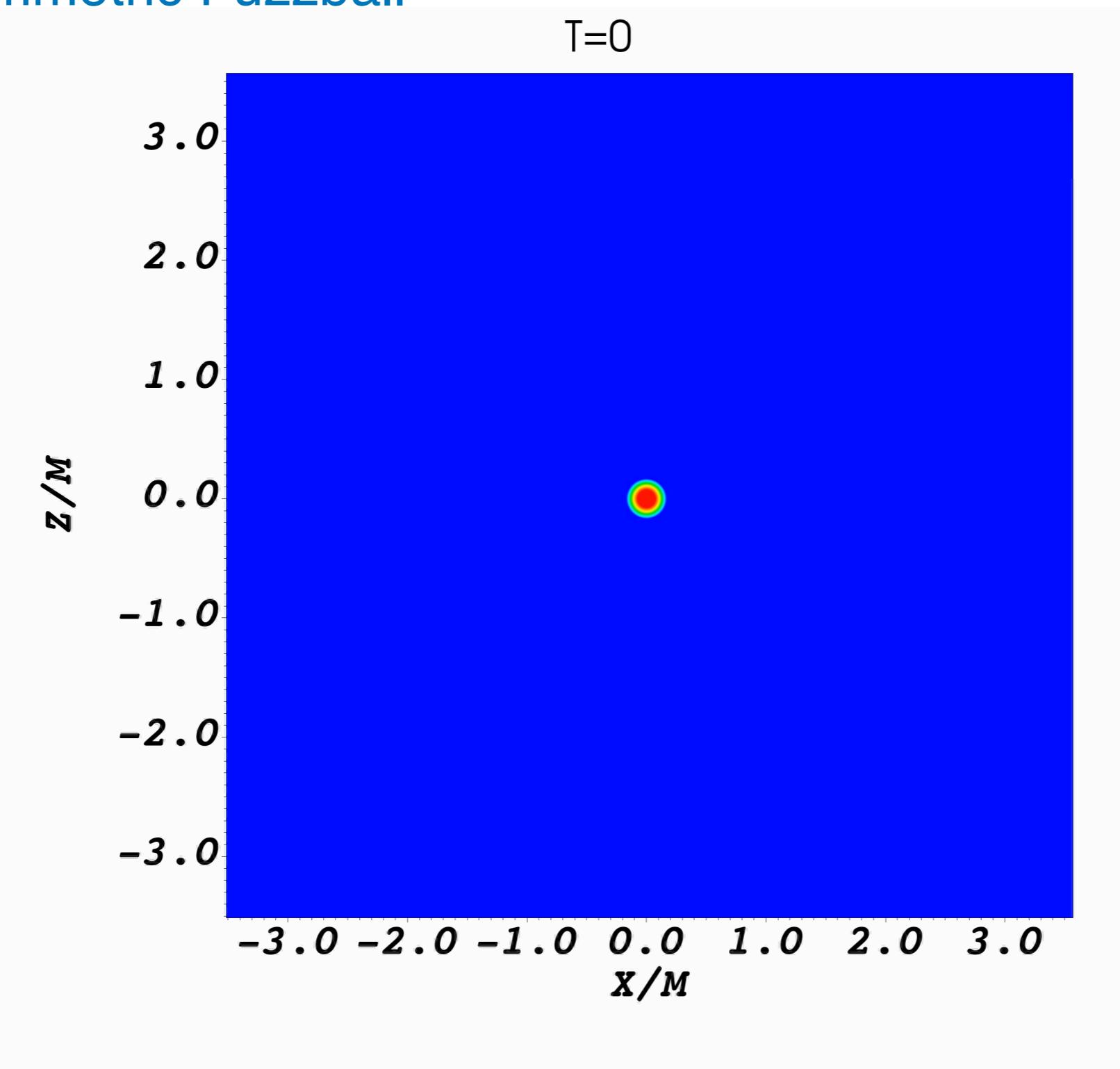
- echo time scale

$$\tau_{\text{echo}} = 2 \int_{r_c}^{r_t} \frac{dr}{dr/dt}$$



3+1 simulations

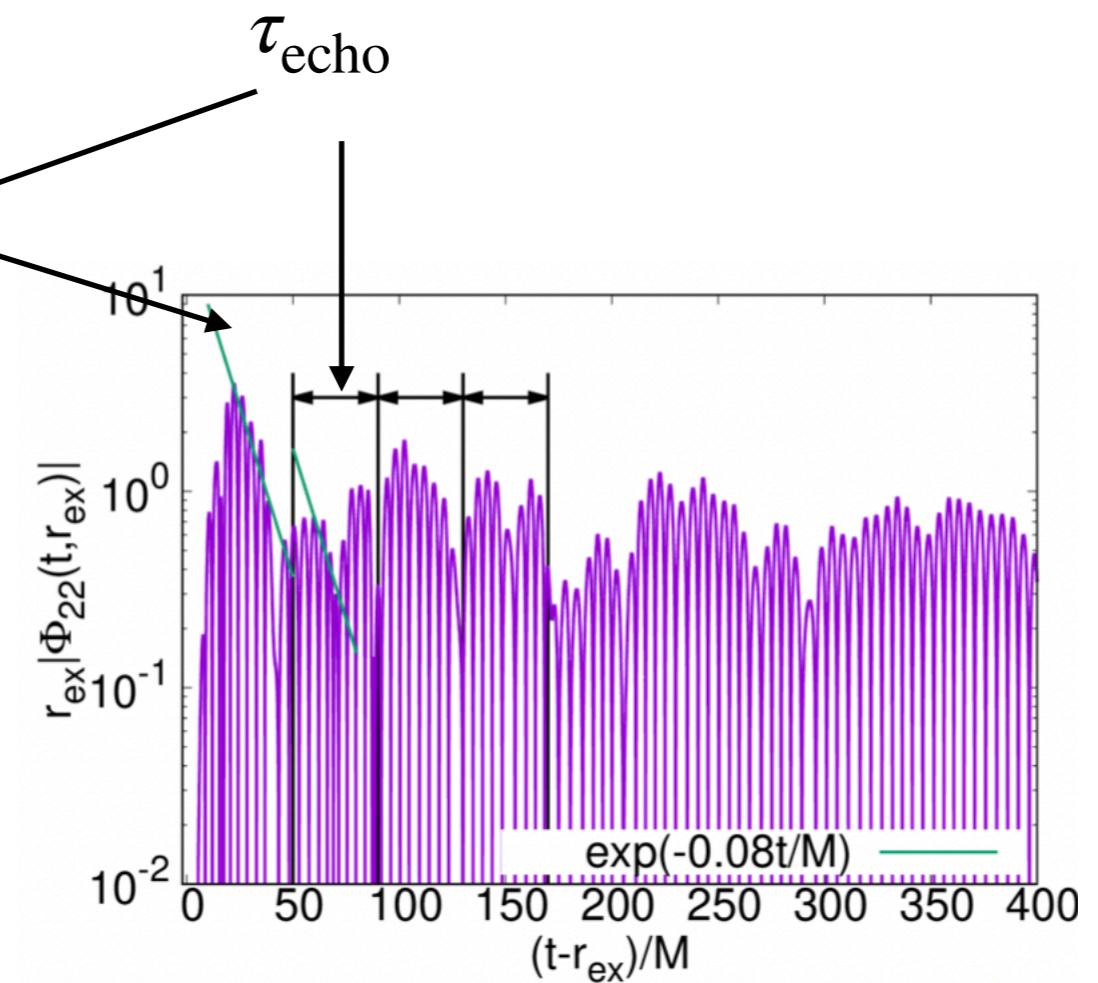
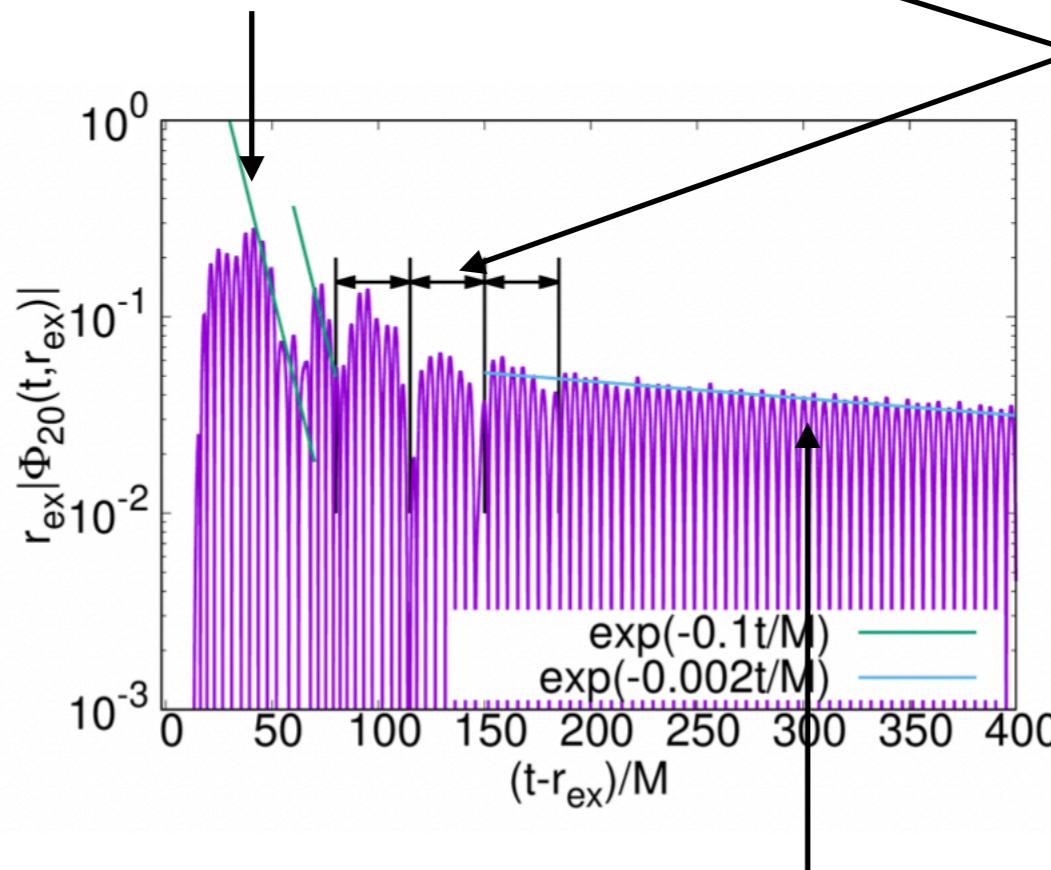
- Axisymmetric Fuzzball



Waveform from Axisymmetric FB

This ringdown is same as QNM of corresponding BHs.

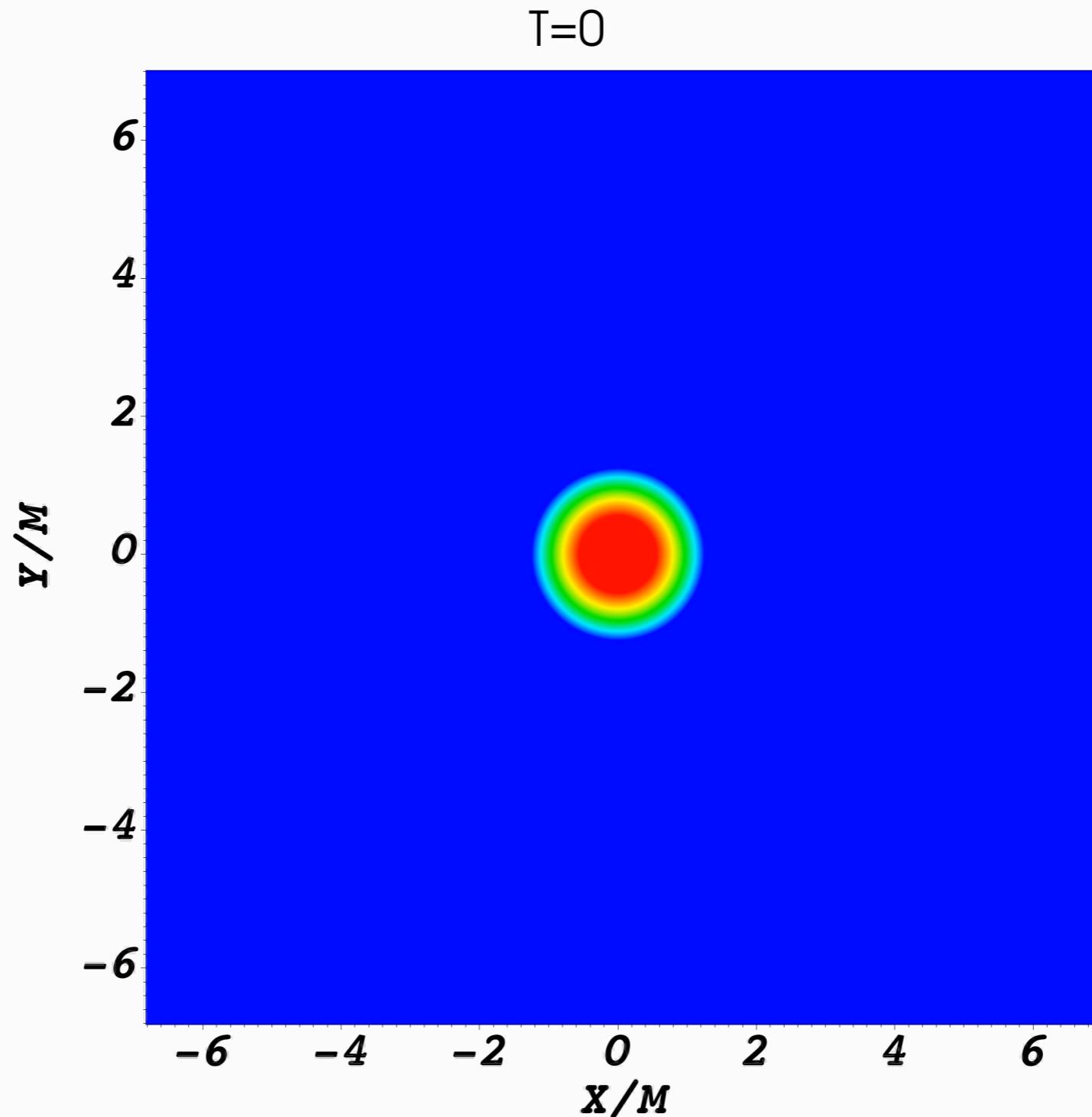
ringdown associated with photon sphere



QNM of Fuzzball

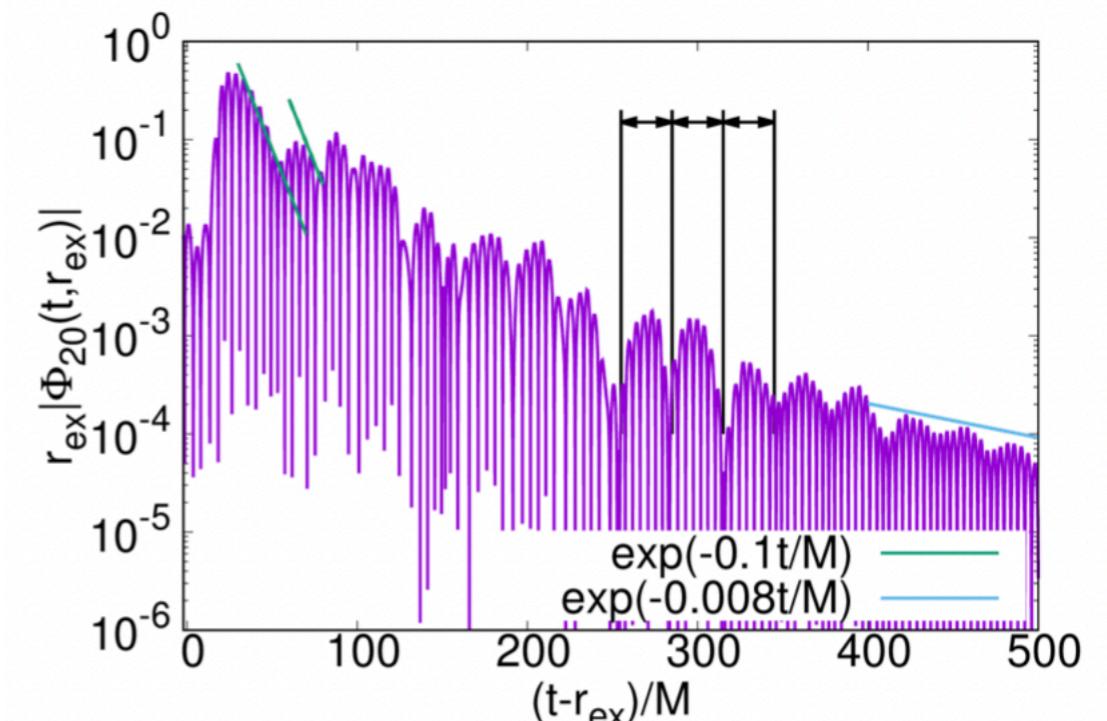
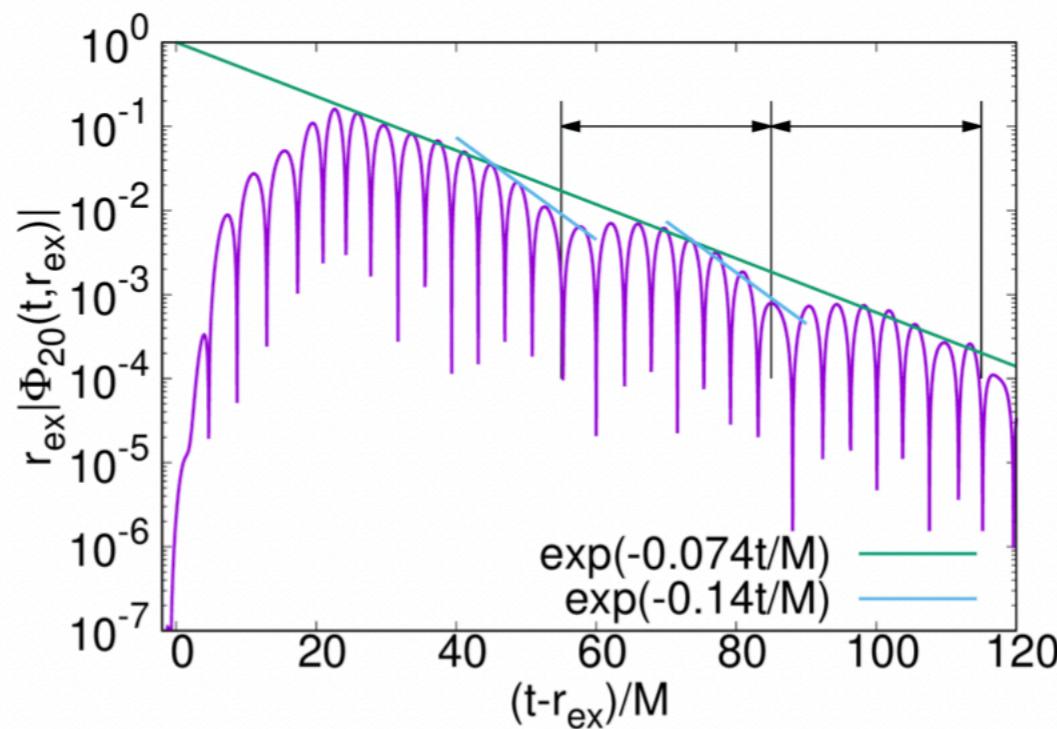
3+1 simulations

- Scaling Fuzzball



Waveform from Scaling FB

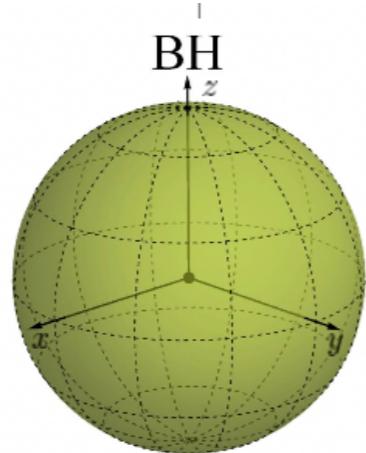
- We obtained the similar behavior around scaling fuzzball.



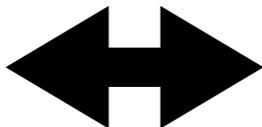
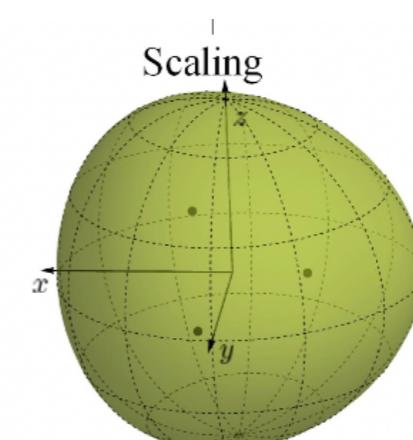
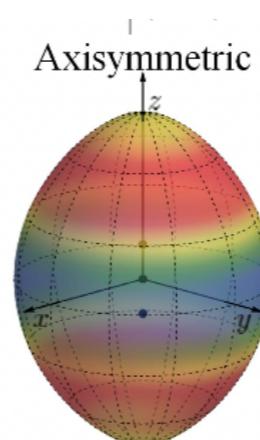
Summary

- We compared waveform from Fuzzball with waveform corresponding BH.

4 charge BH



Fuzzball



- ringdown \longleftrightarrow QNM of 4 charge BH
- echoes \longleftrightarrow WKB approximation (in axisymmetric FB)
- QNM of fuzzball

END